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Mechanical behavior of polyethylene terephthalate/copper composite filament

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Abstract

The majority of polymer materials is electrically insulating for their low values of dielectric constants. A method used to solve this problem is the addition of a conductive metal filament into a polymer filament yarn, which can be directly integrated into a textile. The objective of this work is to identify the mechanical behavior and the friction properties of the polyethylene terephthalate (PET)/copper composite filament. The results of the mechanical tests revealed a ductile behavior of this composite filament. Filaments surfaces have been analyzed after friction with Scanning Electron Microscope. Experimental results show a satisfying wear resistance of filaments.

Keywords: Conductive filament; PET; copper; tensile test; mechanical behavior; friction analyses; polymer surface.

1. Introduction

The development of industrial technology involves a new generation of materials. Among these innovations, composite materials offer an economic alternative and high performances. The use of these materials with specific properties and the development of new structures and integration processes make it possible to develop fabrics able to convey information while being mostly based on properties of electric conduction [1-3]. Lately, two types of conducting polymeric materials have been available, one is extrinsic in nature, where some conductive additives are added to insulating polymer matrix, leading to conducting composites and the other is intrinsically conducting in nature like polyaniline, polyacetylene, polythiophene, polypyrrole, etc…[4-6].

The first type of materials is easily processable to form products of any suitable form. In extrinsically conducting composites electrical properties can be monitored through change in composition that is through control of filler concentration. Thus these systems show wide variation of properties. Different types of conducting fillers like metal powder, flake, carbon black, carbon fibers were used in the past to make different conductive composites [7-9]. Metals were found to be inferior to carbon black with respect to improvement of both mechanical and electrical properties of insulating matrix. High concentration of metal filler is needed to achieve good electrical conductivity

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which makes the system heavy and inflexible. Metal powder does not improve mechanical properties and also acts as a catalyst for oxidative degradation of matrix polymer. Carbon black powder, on the other hand reinforces the polymer especially elastomer matrix preserving its flexibility and light weight, without adversely affecting the environmental and thermal stability of the polymer matrix [9]. The second type of conductive materials, which is extrinsic in nature, offers the desired conductivity. However, it is lacking in process ability, and the scope for manipulation of electrical and mechanical properties is limited [10-12].

The method used in this work is based on the co-extrusion of a conductor filament like copper with a polymer like polyethylene terephtalate (PET). The PET is a polymer that can successfully be recycled, and copper offers good electrical properties [13]. This composite filament can be directly integrated into a textile. However, the filaments may be subject to severe friction during the weaving process, so it could be interesting to analyse the mechanical behaviour and friction properties of PET/copper filaments.

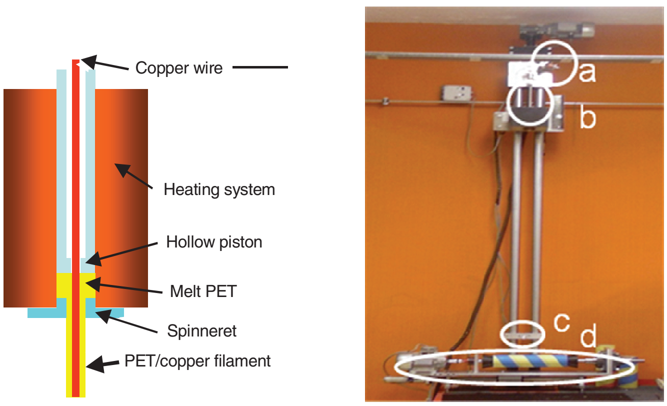
2. Materials and Methods

Three types of samples were investigated in this study; a virgin PET, a copper filament and our produced PET/copper composite filament. The polymer is a virgin PET free from titanium oxide, in the shape of transparent pellets. It is produced and marketed by Rhodia-Filtech (Emmenbrûcke, Switzerland). The characteristics of this polymer are shown in Table 1.

Table 1: Rheological properties of PET

	[η] (dL/g)	M_W (g/mol)	T_f (°C)	MFI (g/10 min)
PET	0.74	42 100	253	20

The copper reinforcement used is a monofilament produced by Goodfellow (purity: 99,9 %) and has a diameter of 50 ± 5 μm. The PET/copper filaments were obtained using a laboratory scale melt spinning under the following conditions: extrusion temperature 280°C, extrusion speed 1-10 cm/min, 2 mm spinneret die dimension, a take up speed of 10 m/min and resident time 5 min. The extrudate was cooled in air then passed through a winding unit (Fig. 1).



(a) Supply copper filament, (b) Hollow piston, (c) Guidance system, (d) Winding unit

Fig. 1: Device for producing the PET/Cu composite filament

The mechanical properties, such as energy of rupture, tensile modulus, strain and stress at break, were measured by using a dynamometer MTS/20. During tensile test, the crosshead speed is adjusted to have break after 20 ± 3 s [14]. A high sensitive sensor of 10 N was used to obtain mechanical data. All tests were performed in controlled temperature room at 65 ± 2% RH and 21 ± 1°C [15].

The friction experiments are performed with a translation tribometer (Microtechnical Swiss Center). Owing to this device, friction measurements were carried out between the PET/Copper filaments, obtained by melt spinning with a diameter of 250 ± 4 μm, and the C38 steel disk with an average roughness less than 10 nm. This apparatus measures the tangential force between the polymer filament and the substrate for controlled normal force ranging 1 N - 8 N and friction speed ranging 10 - 100 mm/min. The tangential force variation has been analyzed and the specimen filament observed by using a scanning electron microscope (SEM – HITACHI S 2360N). This technique allows identifying geometrical characteristics of wear issue from friction between PET/copper filament and steel.

3. Results and discussion

3.1. Analysis of tensile test

In order to identify the performances of filaments, the tensile mechanical behavior of initial copper, PET and PET/Cu composite filaments were analyzed. Twenty-five filaments were tested for each specimen by using a dynamometer MTS/20. The breaking stress (σ_B) and strain at break (ε_B) are obtained at the breaking point and the elastic modulus (E) was calculated from the initial linear part of the stress-strain curves (under 1% of strain). For an individual filament, the energy needs to break (W_B) sometimes called the toughness is defined as the area under the load-elongation curve. The tensile properties of filaments are listed in Table 2.

Table 2: Tensile results for different filaments

	S* (10^{-3} mm^{2})	E (MPa)	ε_B	W_B (mJ/m)	E (GPa)
Copper	n = 90	n = 25			
Mean	1.96	290	0.106	54.57	93.3
Std. D.	0.3	10.4	0.004	2.90	5.05
CV%	15.31	3.59	3.77	5.31	5.41
PET					
Mean	27	25.7	0.016	7.52	1.31
Std. D.	1.6	0.6	0.001	0.268	0.1
CV%	5.93	2.33	6.25	3.56	7.63
Composite	n = 90	n = 25			
Mean	47.2	64.19	0.135	11.6	8.7
Std. D.	1.3	1.5	0.009	0.48	1.1
CV%	2.75	2.34	6.67	4.14	12.64

***Sectional area**

Filaments from virgin PET have lowest tensile mechanical characteristics. These properties are improved by adding in-situ the copper filament. Indeed, the copper filament has the highest mechanical properties. The PET/Cu composite filament shows a ductile behavior and the associated experimental modulus could be verified by the mixture law [16] from the associated modulus of PET and copper. To achieve this, composite theoretical modulus is calculated with values from Table 2 according to the following equation:

$$Eth = \phi PET \, . \, EPET + \phi Cu \, . \, ECu \qquad (1)$$

Where ϕ_{PET} and ϕ_{Cu} are respectively volume fraction of PET and Cu in composite filament. E_{PET} and E_{Cu} are Young modulus for the associated materials taken from Table 2.

According to the equation 1, it can be observed that there is no significant difference between the theoretical modulus E_{th} = 8 GPa and the experimental one E_{exp} = 8.7 ± 1.1 GPa. It appears that the polymer has a good adherence with respect to copper. However the difference between Young's modulus of composite (8.7 GPa) and copper filament (93 GPa) is due to the small section area of the copper filament compared to the composite. Indeed, the section of the composite is 5 times greater than copper.

3.2. Tribological analysis and wear profile

The tribological study concerns the PET/Copper composite filament. The static friction coefficient (μ) between two solid surfaces, PET and steel in our case, is defined as the ratio of the tangential force (F_T) required to produce sliding divided by the normal force (F_N) between the surfaces.

$$\mu = F_T / F_N \qquad (2)$$

For speeds of 10 and 50 mm/min, the friction coefficient is weakly dependent on the normal force, but for higher speed (100 mm/min), there has been a marked increase followed by a decrease after 6 N. Likewise, it is possible that for high-speed, the fixing system filament is not stabilized in the clamps, which could explain the fluctuations. It is also possible that a high speed induces specific mechanisms.

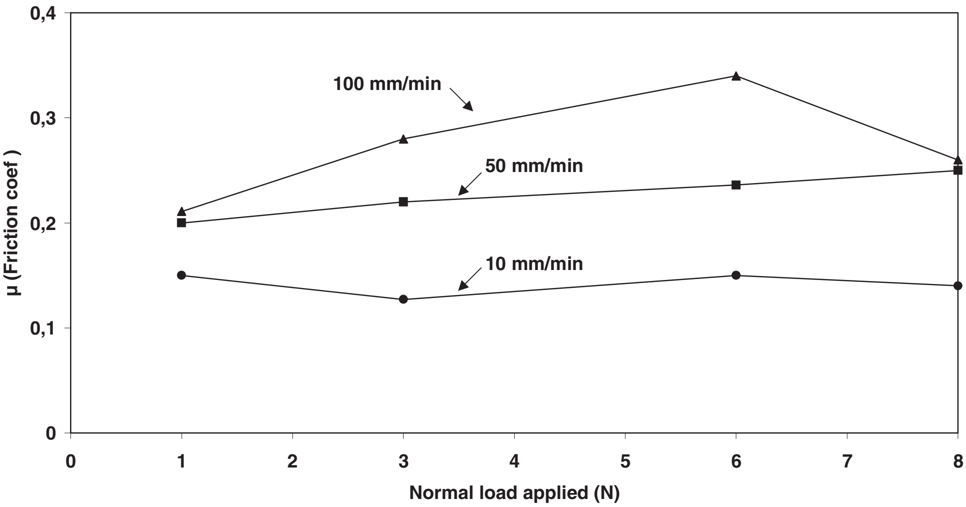


Figure 2. represents the friction coefficient versus the normal force at constant friction speeds.

For an applied constant normal force, it can be noticed that an increase of the friction speed leads to an increase of the friction coefficient. This increase is most important between 10 and 50 mm/min, the values corresponding to 50 mm/min being approximately 1.5 times those of 10 mm/min which can be explained by the viscoelastic dissipation [17]. In fact at 50 mm/min the energy produced by time unit is larger.

We can notice that identical rubbed PET/Cu composite filament at a 100 mm/min speed and with different applied loads show the same wear profile. The eroded area has an elliptical shape and estimated length of 1.5 mm. It could be noticed that the area is flat worn assuming a non-abrasive friction, which is in accordance to the steel roughness. With the help of a more important magnification, the wear particles can be observed (Fig. 3a).

The worn surface has undergone some changes. In fact, thermal effects have altered the surface structure. As shown in Figure 3b, the particles resulting from the wear and present on the scan area are pieces of molten polymer. Under the effect of friction, the particles were separated during the tribological test. These polymer agglomerates are primarily localized on the edges of the worn surface. This confirms the hypothesis that the phenomenon of friction is an adhesive wear [18,19] of the matter and not an abrasive wear.

It can be noticed that we don't see the copper filament at the surface after friction test, which strengthens the hypothesis that copper has a small influence on the tribological behavior of the composite.

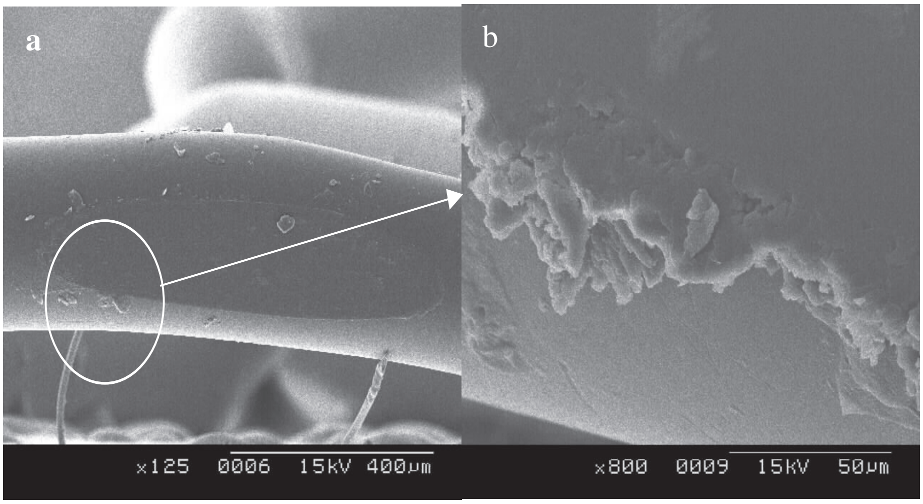


Fig. 3. Scanning electron micrograph of rubbed PET/copper filament. Load: 8 N, V: 100 mm/min, t: 10 min

4. Conclusion

The analysis of tensile test showed a ductile behavior of the composite filament. Filaments from virgin PET have lowest tensile mechanical characteristics. These properties are improved by adding in-situ the copper filament. Indeed, the copper filament has the highest mechanical properties

Friction analysis of PET/Copper filament has revealed two distinct tribological behaviors. The first one when the friction speed is increasing for different normal loads, the friction coefficient tends to increase. This can be explained by a more important viscoelastic dissipation when the speed increases, resulting in an increase in the friction coefficient. The second one shows that the friction coefficient is weakly dependent on the normal load at 10 and 50 mm/min constant speed friction, but for a higher speed (100 mm/min) an increase of the friction coefficient can be observed, followed by a decrease after 6 N. The PET/copper filaments that underwent periods of friction for three hours were observed by scanning electron microscopy. The observation of wear facies has determined that the copper filament has not been reached and that wear on these materials is caused by a warming of matter rather than by abrasion. This study highlights the good quality of PET/Copper interface as well as the good wear behavior of the PET surface filament.

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